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TWO PHASE DETONATION STUDIES RELATED TO ROCKET INSTABILITY—1969

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J. A. NICHOLLS

THE UNIVERSITY OF MICHIGAN

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center
Contract NGL 23-005-336
R. J. Priem, Project Manager

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ANNUAL REPORT

TWO PHASE DETONATION STUDIES RELATED TO ROCKET INSTABILITY—1969

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Ann Arbor, Michigan 48104

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March 11, 1970

Grant NGL 23-005-336

NASA Lewis Research Center
Cleveland, Ohio
R. J. Priem, Project Manager

FOREWORD

This report covers the progress made in the first year, February 1, 1969 to February 1, 1970, on NASA Grant NGL 23-005-336. The study was under the direction of Professor J.A. Nicholls, Department of Aerospace Engineering. Dr. R.J. Priem, NASA Lewis Research Center, was technical monitor.

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TABLE OF CONTENTS

LIST OF FIGURES

ABSTRACT

This report represents an annual progress report on the five phases of the project. Accordingly it describes:

1. The details of the ignition of single fuel drops by a shock wave.
2. The development of a system for producing a controlled distribution of fuel drop sizes in an oxidizing atmosphere for two phase detonation studies.
3. The attenuation of shock and detonation waves passing over an acoustic liner.
4. A simplified theory for the propagation of film detonations.
5. A simplified analytical model of a rotating two phase detonation wave in a rocket motor.

I. INTRODUCTION

The research covered by this annual report represents a continuation of our efforts devoted to the study of detonation waves in liquid-gas systems, such as might occur in liquid propellant rocket motors. The earlier studies were conducted under NASA Contract NASr 54(07) and were summarized in our final report[1] on that project. The research has evolved into five separate phases (A-E) for the present, although all of these are intimately interrelated.

Phase A is concerned with the ignition and breakup times of liquid fuel drops impacted by a shock wave. The pressure overshoots are also of interest. The aim of Phase B is to study a more realistic model of two phase detonation by generating a controlled distribution of liquid fuel drop sizes in a gaseous oxidizer. The earlier studies involved a monodispersed system. Phase C is directed at the possibility of arresting the development of a shock wave into a detonation by means of attenuation in acoustic liners.

In some cases rocket motor combustion instability is affected by the presence of a liquid fuel film on the walls. Accordingly, Phase D is concerned with analytical descriptions of and experiments on so-called film detonations. Phase E is an analytical study of a rotating "detonation wave like" instability which is believed to occur under certain conditions.

The progress made on each phase is now described and the direction for immediate follow-on work is outlined.

II. RESEARCH RESULTS

Phase A - Shock Wave Ignition of Fuel Drops

The study of the interaction of a shock wave with a fuel drop in an oxidizing atmosphere has been continued. In preliminary studies[1] it was found that spontaneous ignition of a fuel drop could occur after interaction with an incident shock wave. The current studies were directed to observing the effects of ambient conditions—Mach number of the incident shock wave, size of the fuel drop, composition and density of the surrounding atmosphere—on the combustion process and its initiation. The effect of the combustion process on aerodynamic shattering of the fuel drop was also observed.*

The experiment was conducted by allowing fuel drops—diethylcyclohexane—to fall through the driven section of a shock tube in which a given ambient condition was maintained. The strength of the incident shock wave was varied between $M_s = 3.00$ and $M_s = 5.00$ while the initial pressure in the test section was set at 10, 20, or 30 in. of mercury. The composition of the ambient atmosphere considered was by mole fraction 100% O_2, 75% O_2 with 25% N_2, 50% O_2 with 50% N_2, 100% N_2, and finally air. The drop diameters used were $d = 932\mu$, 1520μ, and 2130μ.

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*A much more detailed analysis of the work reported below is given in Ref. 2 and 3.

The spontaneous appearance of combustion was not achieved under all test conditions. It was found that a certain minimum strength incident shock wave was required to initiate the combustion process. A typical result of a shock/drop interaction in which no combustion occurs is shown in the streak photograph in Fig. 1. The test conditions are noted on the figure. The interaction in the inert atmosphere simply leads to the shattering of the fuel drop, much along the lines of the water drop shattering reported by Ranger[4]. An interaction in which combustion is initiated by the incident shock wave is shown in Fig. 2. Here it is noted that an intense luminosity appears in the wake of the deforming fuel drop some period of time—ignition delay time—after the shock/drop interaction has occurred. It should be noted that under all of the conditions considered in this study that the combustion has been initiated in the wake of the shattered drop. Stagnation point initiation of combustion has not been observed in any case. It is also seen that the combustion process is accompanied by strong "blast waves". This is perhaps best illustrated in Fig. 3 where the light emitted by the combustion process has been masked out. It is seen that the strong pressure waves which originate in the wake of the burning drop propagate both upstream and downstream subsequently interacting with both the bow and incident shock waves. The strength of these waves may be observed through the response of the instrumentation which is shown in Fig. 4. It is noted that the effect of the blast waves is to increase the pressure by an amount almost equal to that increase caused by the incident shock wave. It was found that by sufficiently diluting the ambient atmosphere with N_2 (50%) this type of detonative combustion could be suppressed. In this case the combustion was not accompanied by the strong pressure waves.

For the detonative type of combustion the ignition delay time was measured for the range of test conditions considered. It was found that the results could be correlated by using an Arrhenius type rate law. That is

$$t_{ig}^{-1} \sim [\text{oxidizer concentration}] \exp(-\Delta E/RT_{03}) \quad ,$$

where the temperature dependence was taken as being determined by the stagnation temperature behind the bow shock. The activation energy was found to vary inversely as the drop radius for a given initial pressure. The values of the activation energies ranged from 7 to 18 kcal/mole.

The effect of the combustion process on the drop break-up was also delineated. It was found that the drop break-up time was increased by from 8% to 14% over that without combustion. Here the break-up time is defined as the period of time taken for the drop to accelerate to 0.6 of the convective flow velocity behind the incident shock wave. However, it was found that the break-up time was still inversely proportional to the square root of the dynamic pressure as was the case for non-reacting fuel drops.

Efforts are now underway to develop a suitable analytical model to describe the process by which a fuel drop surrounded by an oxidizing atmosphere is spontaneously ignited by an incident shock wave. A few experiments are being conducted on a different fuel (n-hexadecane). Also calculations will be made on the size of drops in the microspray.

Phase B - Energy Release Rates

To date, our experimental studies of two phase detonation have considered monodisperse systems (liquid drops all of the same size). Attention was given to the pressures developed, reaction zone thickness, propagation velocity, and the influence of drop size and mixture ratio. It was found that pressures and heat transfer rates well in excess of that expected from an equivalent all gas detonation were experienced. Now in a real system there will, of course, be a distribution of drop sizes. Undoubtedly this will lead to appreciable alterations in ignition time delays, reaction zone structures, and transient pressure and heat transfer peaks. Accordingly, efforts have been expended to "build-up" a distribution function for drop size by producing a few discrete drop sizes simultaneously. This has resulted in equipment modification and development work on a variable drop size generator. These efforts are now described.

The vertical detonation tube facility has been largely rebuilt and modified to accommodate the spray detonation, film detonation and acoustic liner studies with minimum changeover. Part of the new setup is shown in Fig. 5. The heavy table behind the "lower viewing section" is one of two adjustable platforms which support lathe beds used as optical benches for the photographic studies. Also shown in the figure is the control room patchboard which links to another at the detonation tube to permit simplified data acquisition changes.

A polydisperse droplet generator has been designed and built. In this system, a polydisperse spray is produced by physically adding two or more monodisperse sprays, and hence it relies on principles that have been previously exploited in our two-phase detonation studies. To produce a spray of droplets of nearly uniform size, a cyclical disturbance is applied to a free liquid jet having a circular cross section with diameter approximately half that of the droplets desired. In our application, the jet issues vertically downward from a capillary tube and the drops produced are allowed to fall freely. The theory on which this method is based is taken from Ref. 5; the technique has been described in Ref. 6 and 7.

The polydisperse generator is shown in Fig. 6 and 7. Twenty capillary tubes having arbitrary I.D.'s up to 0.053 in. and uniform O.D.'s of 0.063 in. are arranged in an array bounded by a 1 in. square centered over the detonation tube. These "needles" are supported in the generator head by two O-rings (through which they pass) and remain stationary.

The fluid flow through each individual needle is carried by a 1/16 in. O.D. flexible plastic tube which passes through a vibrating platform. The oscillatory disturbance introduced into the fluid in this way is transmitted to the jet issuing from the needle.

Theory shows that the growth in the free jet of an oscillatory disturbance at a particular frequency varies with the velocity of the jet. The jet velocity for maximum disturbance growth is a function of capillary diameter. Hence, to achieve the most efficient breakup of each jet when two or more different droplet sizes are to be generated at the same time, individual control over the mass flow through each capillary is required.

This control is exercised in the generator system by means of very fine metering valves. The mass flow through each needle is measured by observing the drop in static pressure across it (see Fig. 7 and 8).

The ideal vibrator frequency would be such that for each needle diameter within the desired range, the mass flow through the capillary could be set so as to obtain maximum disturbance growth in the issuing jet, and at the same time satisfy the following two requirements:

1. It should be above that for which "dripping" occurs. Dripping results when the work done by the surface tension of the fluid at the lip of the needle is able to absorb the kinetic energy of the emerging stream.

2. The velocity of the droplets formed should be below or equal to their terminal free-fall velocity, at the generator head, to deter coalescence of successive drops, and the drops should be very close to their terminal velocity when they reach the position in the detonation tube at which measurements will be taken.

These requirements can be reasonably met in the formation of all DECH droplets having diameters in the approximate range $290\mu < D < 2600\mu$. In this range, the drag law for the falling drops ($10 < Re < 1000$) can be taken as $Re^{1/2} C_D = 9.64$, and it can be shown that at the frequency

$$f^* = 0.112 \left(\frac{\rho_\ell^2 g^2}{\rho_g \mu_g} \right)^{1/3} ,$$

every droplet will be at its terminal velocity when it is formed, provided the mass flow through each needle is set for maximum growth of the disturbance at $f = f^*$. For DECH droplets falling in a pure O_2 atmosphere at 14.7 psi, the value of this special frequency is $f^* = 1450$ cps.

Figure 9 shows four streams of DECH droplets being formed simultaneously by the polydisperse generator. The photograph was taken approximately 2 in. below the generator head.

In Fig. 10, the effect which the oscillatory disturbance has on the jet breakup is confirmed. The jet breakup is highly irregular at all times in the absence of the vibration.

After being formed, the droplets fall in a straight line for about 1 ft, after which their trajectories become increasingly random. Some coalescence results from collisions between drops, and some droplets are lost when they strike the wall. Neither of these problems is very pronounced. However, as will be observed in Fig. 9, droplets formed at $f = f^* = 1450$ cps follow one another by approximately 2 diameters, and coalescence within the first few feet of the free fall can occur if the reduction in drag on a given droplet due to its presence in its predecessor's wake causes it to accelerate.

This difficulty is considerably alleviated, as was done in the case of the monodisperse generator, by providing a gas flow coaxial with the fluid jet at the needle exit. This produces intensified local turbulence which prevents the droplets from falling behind one another long enough for them to coalesce from the wake-following effect.

Figure 11 shows the effect of the presence of the coaxial flow on the droplet size distribution measured 7 1/2 ft below the generator head.

Without the coflow, the distribution is wider and peaks approximately 35% higher than when the coflow is used. The predicted peak in this case was 288μ.

Figure 12 illustrates an application of the generator. Three distributions were created, two "monodisperse" and one bimodal. Coflow was used in all three cases. The two monodisperse sprays were generated independently, and then simultaneously to produce the bimodal spray. Four needles of each of the two sizes were employed.

Detonation waves propagating through such mixtures will soon be generated and the major features of the reaction zone assessed.

Phase C - Acoustic Liner Studies

Other phases of this study have pointed to the ease with which two phase detonation waves can be generated and how the droplet-convective flow-ignition interactions and resultant pressure pulses maintain the wave. Such phenomena are ordinarily deleterious to rocket motor performance and the aim of this phase of research is to ascertain whether acoustic liners could arrest the development or maintenance of these waves. Some experiments have been conducted on the passage of shock and detonation waves over an acoustic liner and an approximate analysis has been initiated. These efforts are now described.

Experimental Studies

The photographic observation of shock waves of various strengths passing over an acoustic liner was continued. Spark shadowgraph and spark schlieren pictures indicated the diffraction pattern of the incident shock wave and the occurrence of secondary waves at the entrance to the cavities of the Helmholtz resonator as the gas behind the shock flowed into the cavities. Distinct vortices formed at the entrance section of the cavities. These vortices moved into and dissipated within the cavity. The secondary wave systems from adjacent cavities interacted and, in some cases, back flow from the cavities into the tube was observed. The reduction in shock velocity was observed to be small[1].

The present vertical detonation tube set up also allows fully developed or developing detonation waves to enter the acoustic liner test section under controlled conditions. This allows the wave speed to be measured as a function of the initial wave speed, drop size, mixture ratio, and cavity size. With this arrangement it is possible to determine the extent of attenuation possible with different strength detonation waves and liners and visualize the interaction phenomena.

Preliminary tests were conducted to observe the interaction of the detonation wave and the acoustic liner. A detonation was generated employing a single stream of 2600μ DECH drops in oxygen (equivalence ratio of $\simeq .25$), which resulted in a wave velocity of approximately 3000 fps at the beginning of the test section, which is about 6 ft below the injection point. The earlier experiments[8] indicated that this wave continues to accelerate and reaches a velocity of 3500-4000 fps at a point 12 ft below the injection point. In the presence of the liner (1 in. diameter cavities spaced 1 1/8 in. apart) there appeared to be no appreciable increase in velocity across the test section, and beyond the test section the wave accelerated. However, within the test section itself the velocity went through a cycle of decrements and increments ($\simeq$ 200 fps) when the wave passed over the cavities.

The above types of experiments, along with tests using shock waves instead of detonation waves, will be conducted for a range of wave strengths, drop sizes, equivalence ratios, and liner geometries. Observation of the interaction of the wave with the liner will be made using spark shadowgraph, spark schlieren, and streak schlieren photography and high frequency response pressure instrumentation. However, before proceeding with these rather extensive tests it was deemed advantageous to effect a simplified theoretical analysis which would serve to estimate the attenuation of a shock wave passing over a Helmholtz resonator. Sufficient weakening of the shock could preclude formation of the detonation wave.

Analysis

In an ideal shock tube (that is, neglecting wall and real gas effects) the shock wave and the contact surface both move with a constant velocity and the flow between them is uniform. However, a Helmholtz type reso nator placed between the shock wave and the contact surface acts as an aerodynamic sink, removing mass from the region between the shock and the contact surface. This mass removal causes the shock to decelerate. A rigorous treatment of this problem is quite formidable and not warranted at this stage of the investigation. The present interest is to establish orders of magnitude and to identify the major parameters.

The approximate analysis proceeds as follows. The initial shock strength (at entrance to the acoustic liner section), the liner geometry, the test gas, and the distance to the contact surface from the shock are assumed given. The shock motion is treated as quasi-steady and the coordinate system attached to the shock so that the walls (and liner cavities) move past at the shock velocity. The normal shock relations are then applied to determine the conditions immediately downstream. Some of the flow behind the shock flows through the orifices and into the liner cavities. This mass flow is estimated by assuming a one-dimensional isentropic flow from the stagnation conditions of the convective flow to the static conditions in the Helmholtz resonator cavity. The convective flow is at right angles to the axis of the resonator orifice. It is reasonable to use the static pressure instead of the total pressure in the convective flow. However, available engineering data[9] on the coefficient of discharge for orifices with approach flows perpendicular and inclined to the orifice axis use the duct total pressure as the reference to determine the ideal jet velocity in the orifice. Also these discharge coefficients are measured for steady flow conditions whereas the flow from the shock tube into the resonator is time unsteady. Under these conditions the resonator orifice acts as an isentropic nozzle operating between the total pressure of the convective flow and the instantaneous cavity static pressure. It is assumed that the kinetic energy of the cavity flow is wholly lost, while the mass addition increases the cavity pressure by isentropic compression. The flow into the cavity is assumed to cease when the cavity pressure attains the static pressure of the free stream. Any regurgitation of flow into the convective flow is neglected. The total mass flow into the cavities is then determined (perhaps by numerical integration). The residual mass flow rate is assumed to pass through the contact surface (one dimensional basis). This gives an altered velocity into the contact surface from which a new shock velocity can be calculated. This process can then be repeated successively to arrive at the variation of shock velocity with time.

Numerical results using the above described procedure are not available at present. The predictions, when available, will be used to guide and interpret the experimental phase.

Another planned approach, not initiated as yet, is to apply techniques that have been used in the study of attenuation of boundary layers[10-12], wherein the boundary layer is sometimes replaced by a distribution of aerodynamic sinks. In the present study it would be necessary to use a distribution of sources and sinks with their strengths oscillatory with time (due to the inflow and outflow from the cavities).

Phase D - Film Detonations

A simple analysis of the propagation of film detonations has been developed. The theoretical model assumes that vaporization is the rate limiting process, and that the boundary layer behind the initial shock is turbulent. An empirical boundary layer analysis then leads to values of reaction zone length and propagation Mach numbers in reasonable agreement with the measurements of Ragland[13], although the final pressure is considerably higher than the observed value. The results of this analysis are being prepared for publication, and have been submitted for possible presentation at the Thirteenth Symposium of the International Combustion Institute.

A more precise analysis taking the boundary layer-free stream interaction within the reaction zone into account has been formulated. Two approaches are being considered. In the first the effect of the boundary layer upon the free stream flow is determined by establishing the effect of the boundary layer displacement and momentum thickness upon the free stream or core flow. In the second approach the influence of the boundary layer is taken into account via the effects of heat and mass transfer and skin friction on an assumed one dimensional flow within the detonation tube. In order to calibrate the first, or displacement thickness, method velocity deficits are being computed for gaseous detonations, for then the results can be compared with the similar analysis of Fay[14].

The experimental apparatus used in film detonation measurements has been rebuilt in order to make more rapid data acquisition possible. New data has been obtained for DECH-oxygen film detonations. The results are in reasonable agreement with the simple film detonation theory and with Ragland's results in those regions of equivalence ratio where the two sets of data overlap.

Phase E - Theoretical Analysis of a Tangential Two Phase Detonation

The analytical calculations associated with rotating detonation wave combustion instabilities have been carried out in two steps. The first step involved an analysis using a very simple model of the overall process to test the validity of the assumptions and to gain insight into the magnitude of relevant parameters. The second step, which is in progress, consists of setting up a more realistic model from which predictions of detonation parameters can be made, for given input conditions.

It should be noted that in wall fixed coordinates, the gas dynamic problem is unsteady due to the rotating wave. However, if coordinates are attached to the wave, which is assumed to rotate at a constant angular velocity, and if frictional and heat transfer effects at the wall are neglected, the problem is that of a steady flow with a standing wave. Propellant droplets enter the region under consideration with the given injector velocity as the axial velocity component and with the wave velocity as the tangential component, since in the wave fixed coordinate system the chamber is rotating with tangential velocity equal to the wave velocity. Finally, since only annular motors, or thin annular sections near the injector plate and the outer chamber walls, are considered, the annulus may be "unrolled"; then the problem reduces to consideration of a two dimensional steady flow with the cyclic aspects being reproduced by forcing the tangential flow to pass through a detonation wave each time it has traversed a distance equal to the annulus circumference.

The first calculation was for a very simplified model in which the incoming propellants were assumed to be cold gases which did not mix with the hot products of combustion. In addition, it was assumed that the high pressure immediately behind the detonation wave blocked the injectors and that this blockage existed until the pressure had dropped to its minimum value, where it stayed until the next detonation wave was reached. Gradients in the axial direction were neglected and the mass velocity in the axial direction was assumed to be constant. The wave was taken to be a Chapman-Jouguet detonation wave. Calculations were made for the pressure variation in the tangential direction, using experimentally[15] found values for the pressures immediately in front of and behind the detonation waves. These calculated pressure distributions agreed very well with those found experimentally. This work was presented at the 6th Annual ICRPG Meeting[16].

Presently work is proceeding on a more complicated, more realistic model. First, it was determined that for propellant droplets above roughly 10 microns in diameter, that drag and heat transfer effects are negligible, so that gas-droplet interactions may be ignored. In addition, by comparing typical wave periods with typical characteristic vaporization times, it was found that there are propellants which suffer very little vaporization during a wave period. Hence, in the present model the combination of conditions leading to insignificant interaction between the droplets and burned gases, with insignificant droplet vaporization, is assumed. Later, some evaporation will be allowed. All reaction is assumed to take place as a result of droplet shattering and subsequent ignition behind the shock part of the detonation wave, and to be contained in a thin region behind the shock. The detonation is taken to be a Chapman-Jouguet wave due to the pressure relief which takes place immediately behind the wave. In the region between detonation waves, the pressure and temperature of the burned gases are assumed to vary isentropically since friction and heat transfer and droplet interaction are negligible, and any shock waves entering the region are relatively weak (otherwise they would start detonation waves).

The jump conditions across a wave traversing a mixture of gas and droplets, each with different velocity magnitudes and directions, have been derived, and it has been demonstrated that although the detonation wave is not exactly normal to the wall at the wall, it is very nearly so. Hence a normal detonation wave has been considered.

The propellant droplets can travel axially a distance equal to the product of their axial velocity component and the wave period before they enter a detonation wave. Hence for axial distances greater than this droplet travel, the transverse wave is no longer a detonation, but a shock wave. The character of the shock-detonation wave intersection is being investigated, there being more than one possibility. In addition, the shape of the interface which passes through this intersection and which separates the burned gas behind one detonation wave from the burned gases behind the previous detonation wave is being calculated by approximate methods. For a given set of conditions, more accurate calculations can be made by using the method of characteristics.

Finally, the jump conditions, the isentropic relations, and the general conservation relations which hold between waves are being solved in an attempt to relate wave velocity and conditions in front of the detonation wave to propellant and engine parameters which would be known in any given case.

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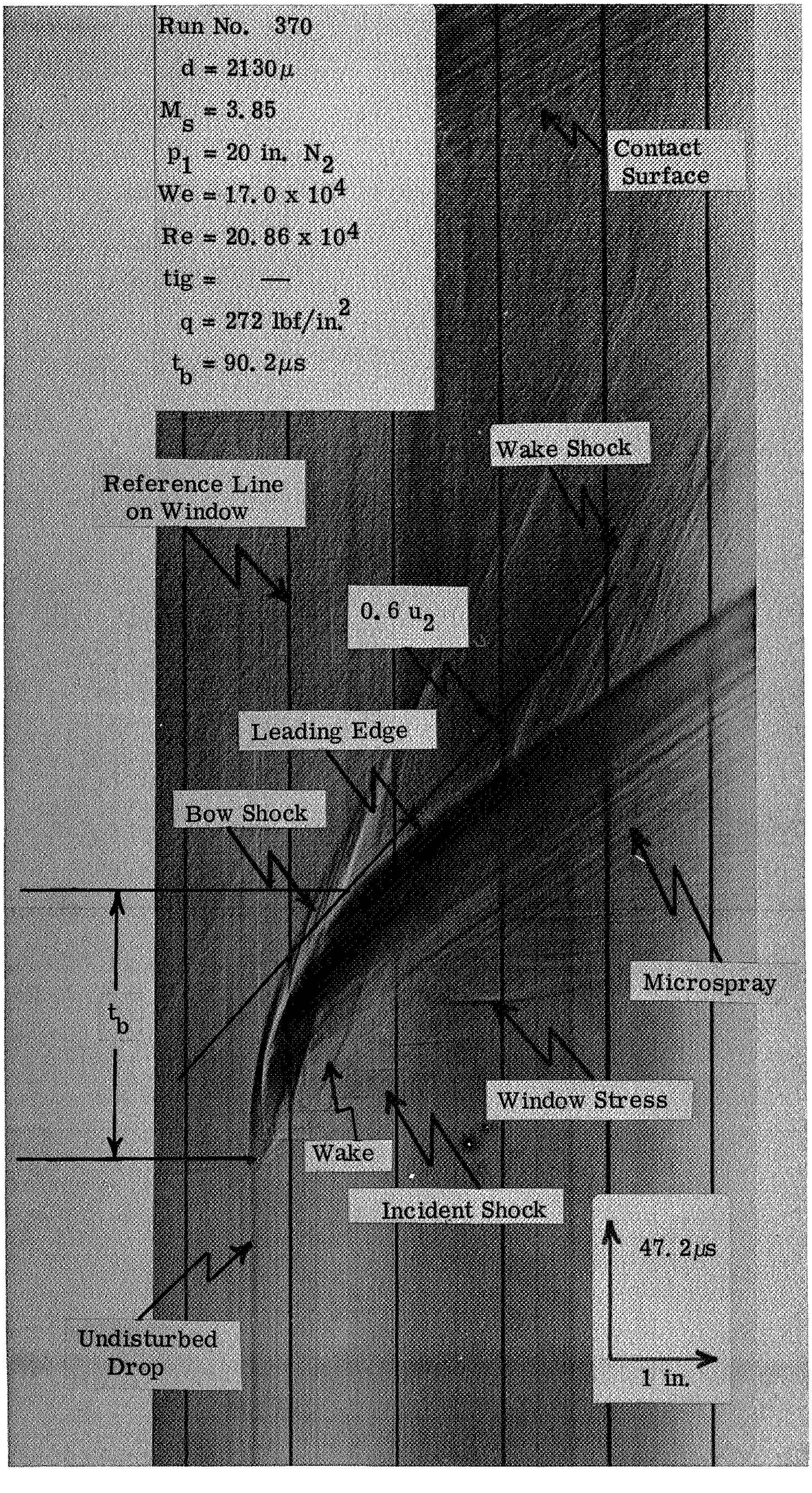


Figure 1. Non-reacting Drop.

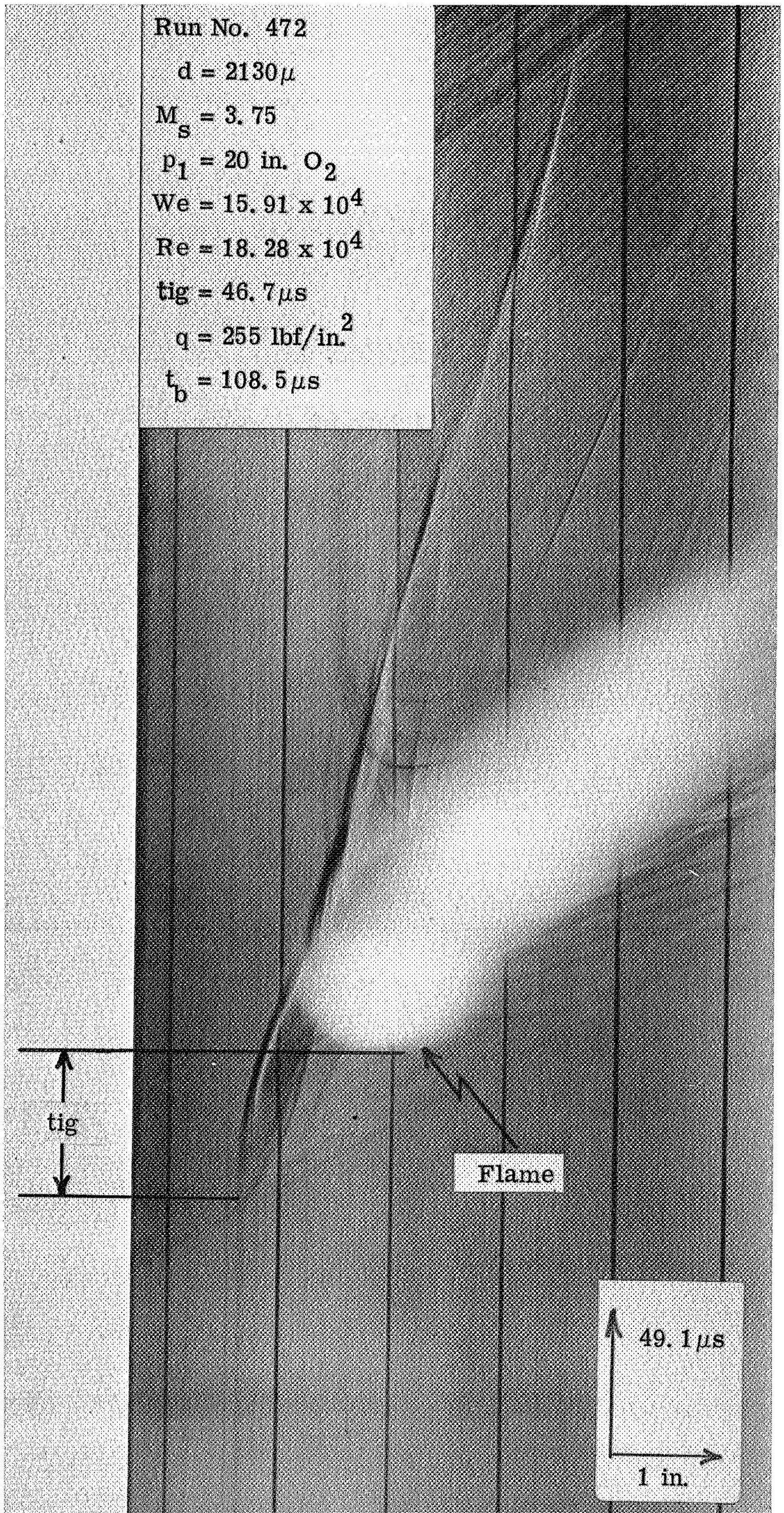


Figure 2. Reacting Drop.

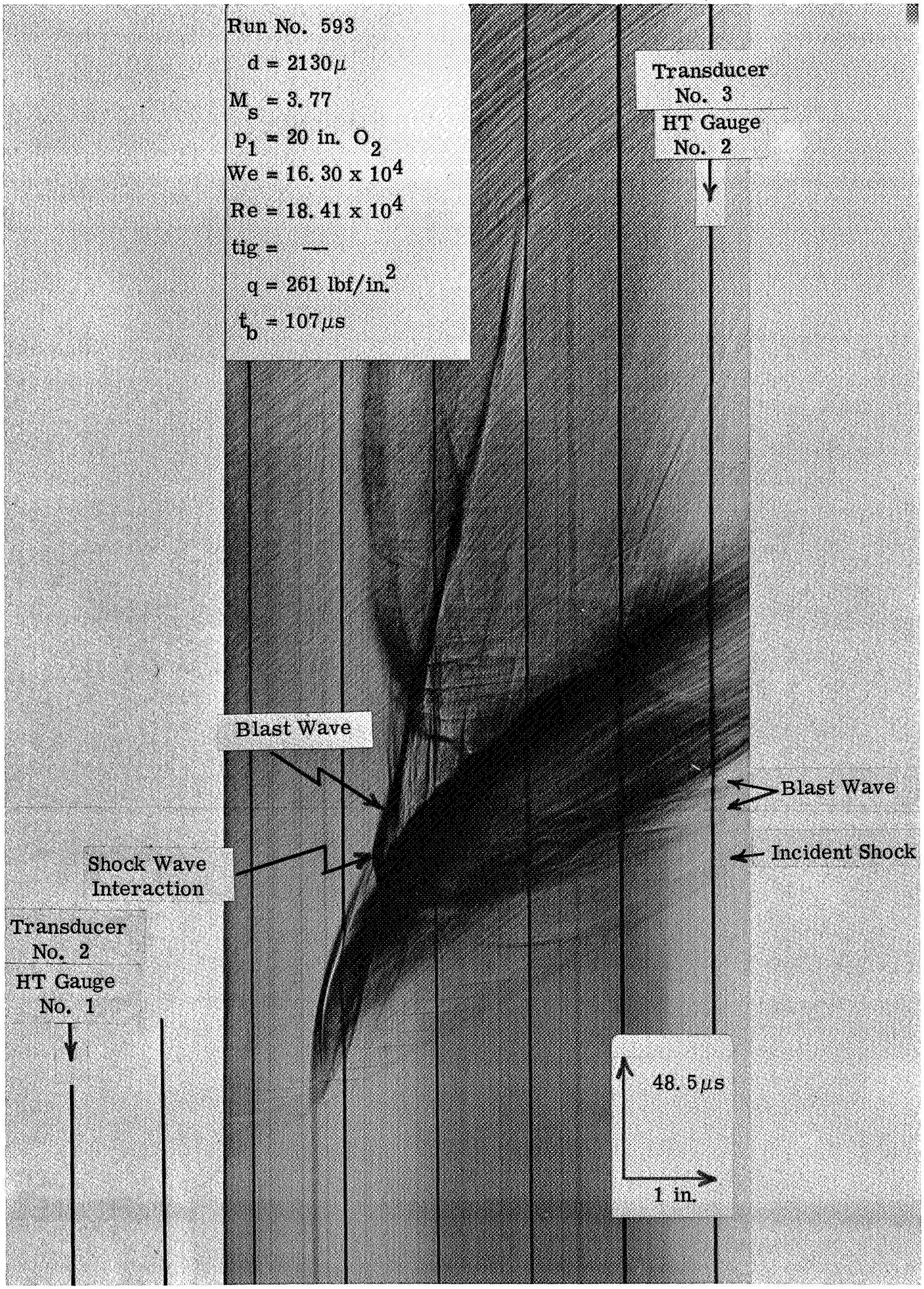
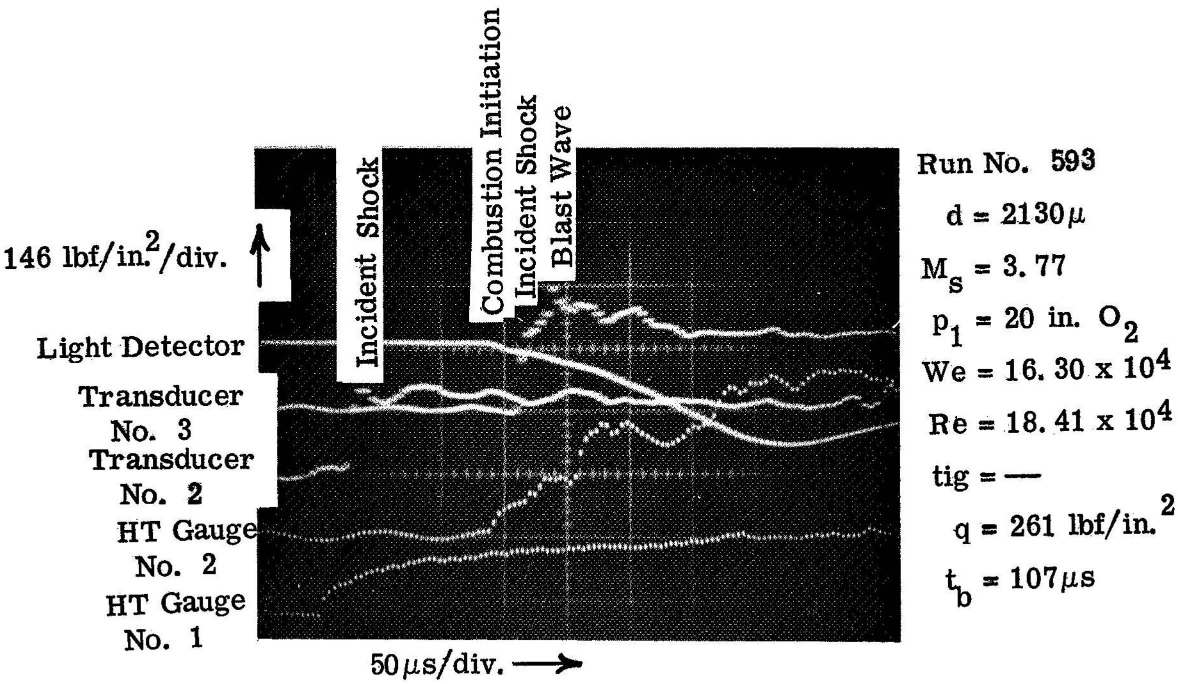
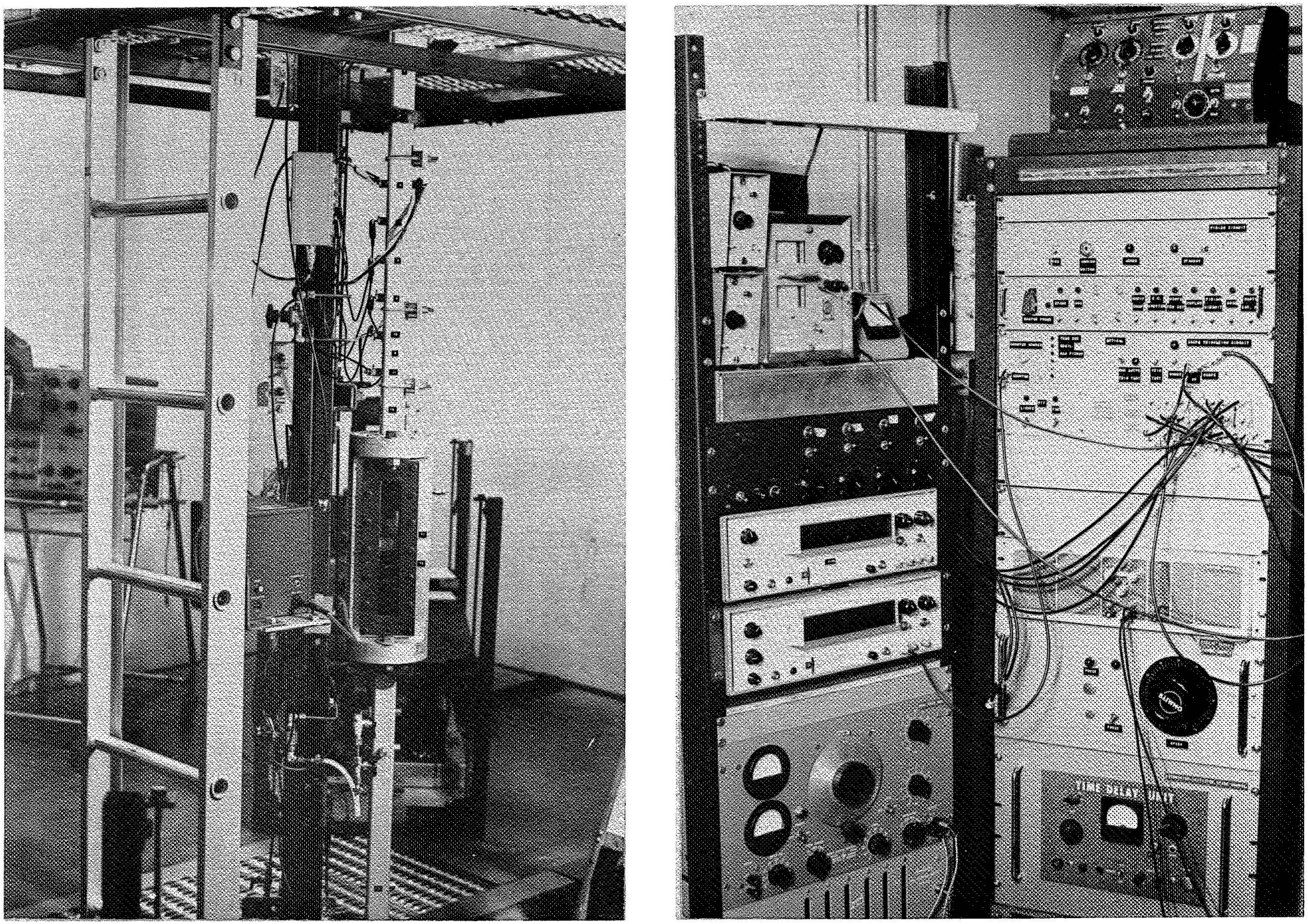


Figure 3. Reacting Drop—No Emitted Radiation.



Heat Transfer and
Pressure Record

Figure 4. Heat Transfer and Pressure History.



(a) Test Cell (b) Control Area

Figure 5. Experimental Arrangement.

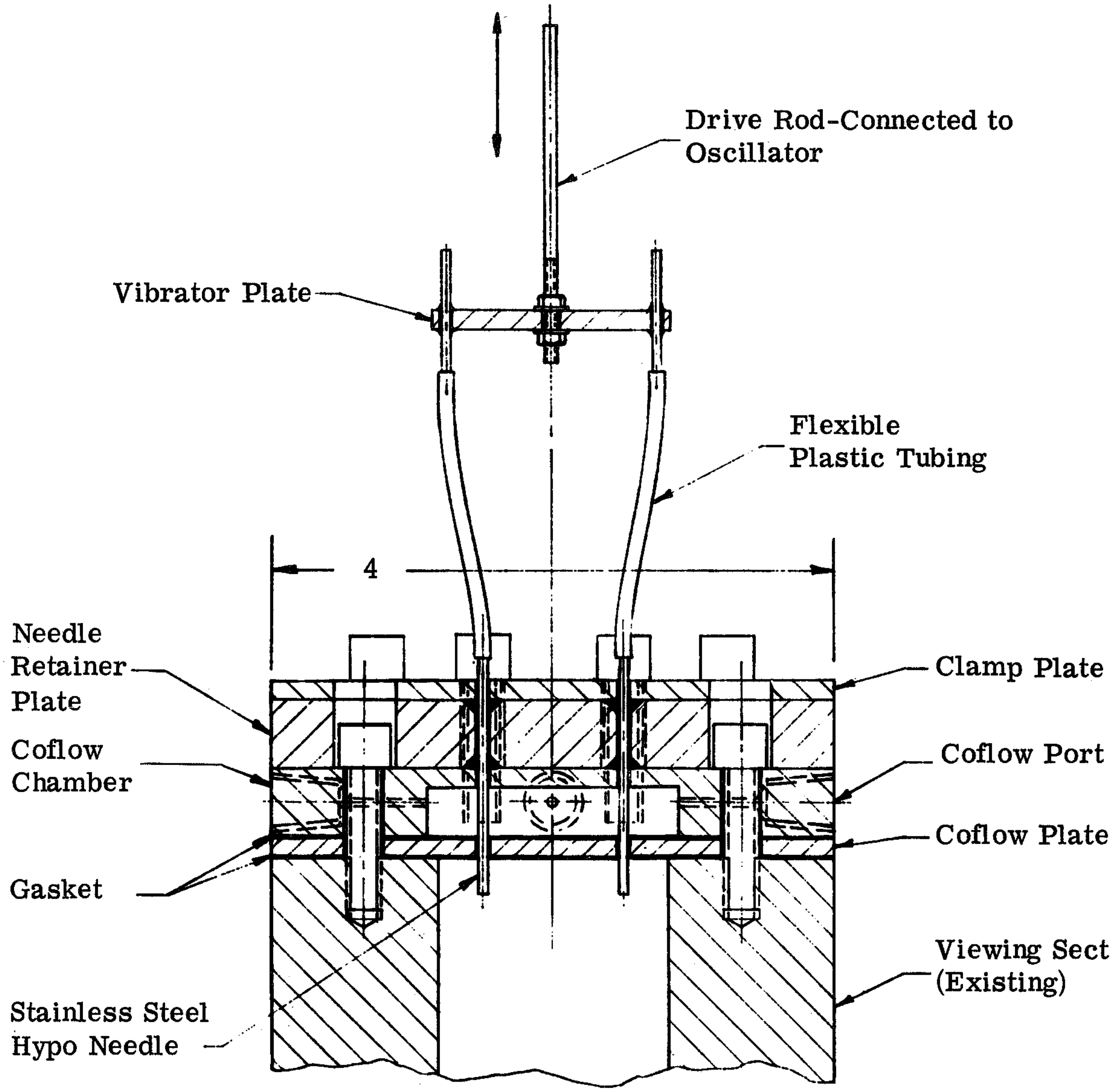


Figure 6. Drop Generator Head Detail.

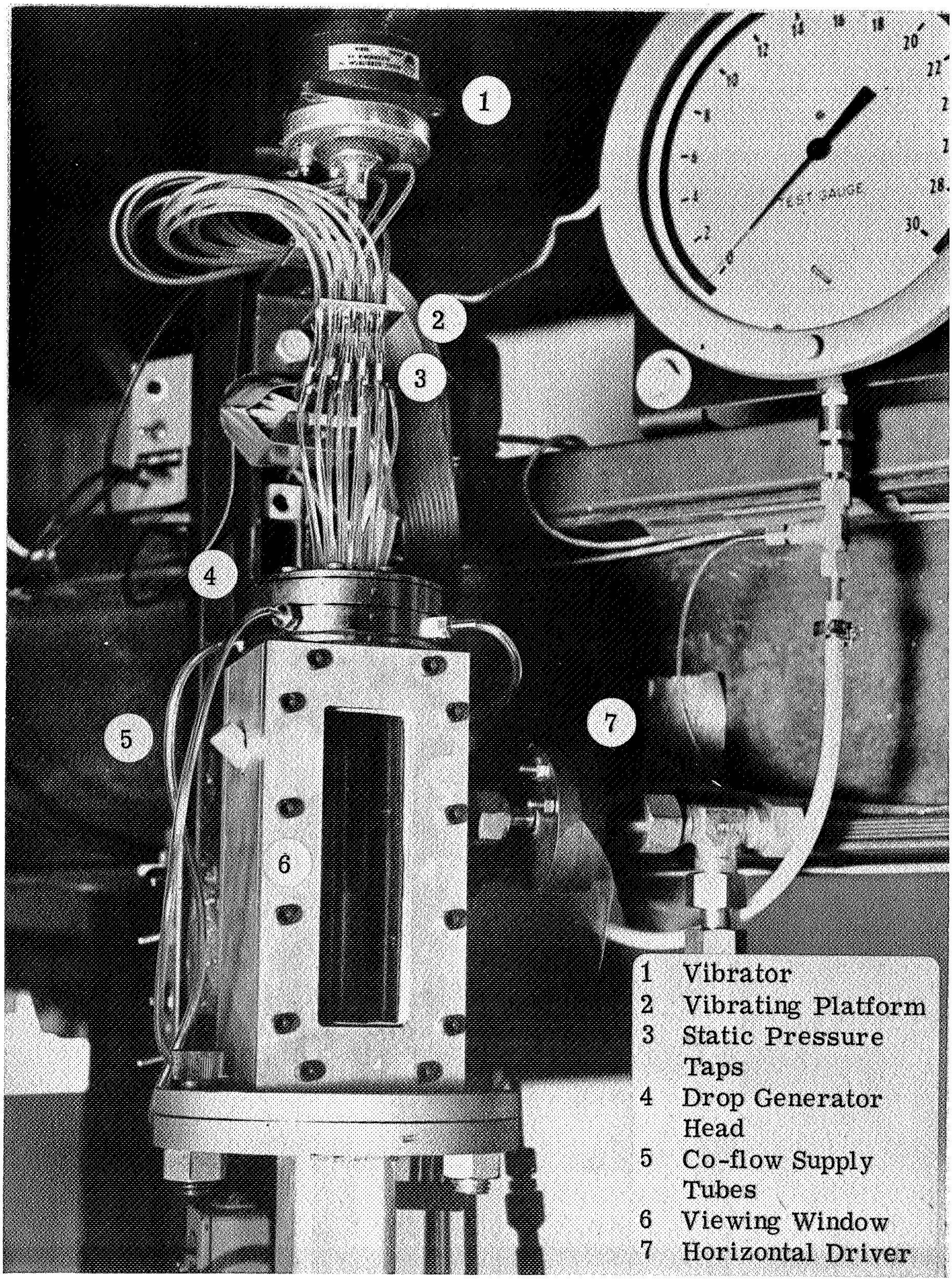


Figure 7. Drop Generator Assembly.

A Nitrogen Supply

B Two Stage Regulator

C Unfiltered Polyethelene Fuel Reservoir

D Reservoir Vent

E 5 Micron Fuel Filter

F Pressurized Stainless Steel Supply Bottle

G Supply Bottle Level Indicator

H System Drain

I Supply Bottle Vent

J Supply Pressure Gage

K Hydraulic Fuel Manifold

L Supply Solenoid

M Bleed and Manifold Pressure Dump

N Toggle Valve

O Metering Valve

P Fine Metering Valve

Q Drop Generator Head

R Oscillator

S Oscillator Platform

T Static Pressure Taps

U 20-Position Valve

V Needle Static Pressure Gage

W Bourdon Tube Bleed

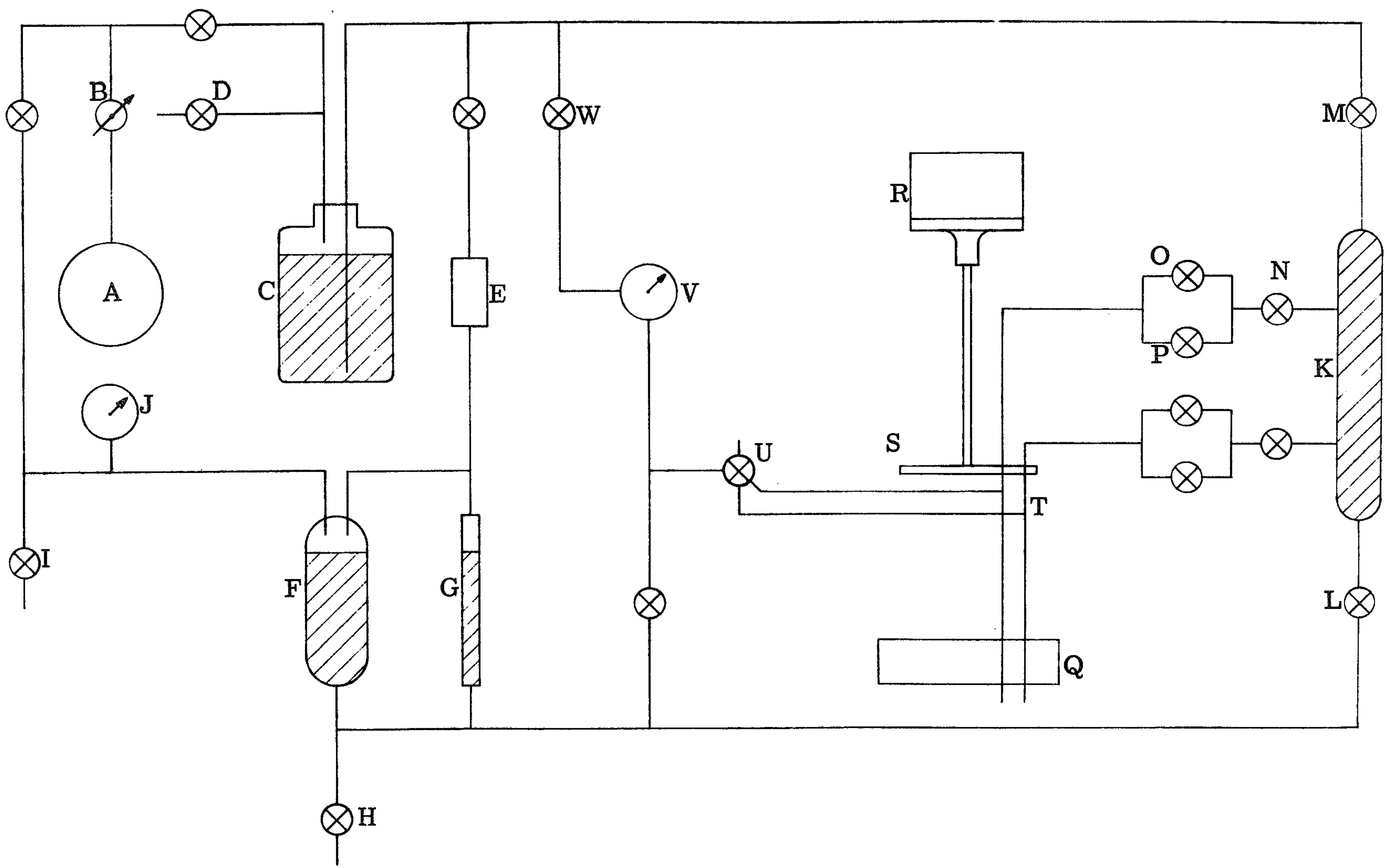


Figure 8. Schematic of Drop Generator Fuel Supply, Metering System, and Needle Pressure Drop Measurement System.

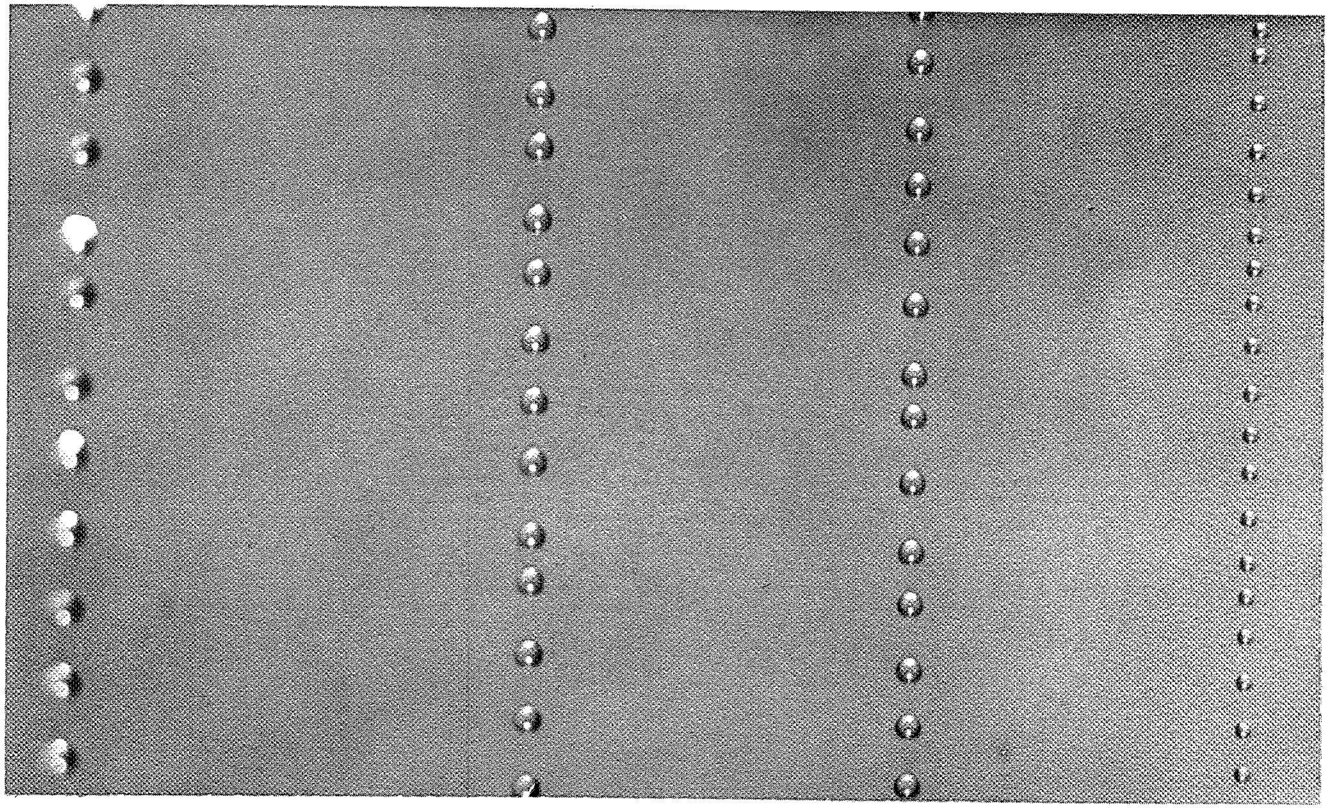
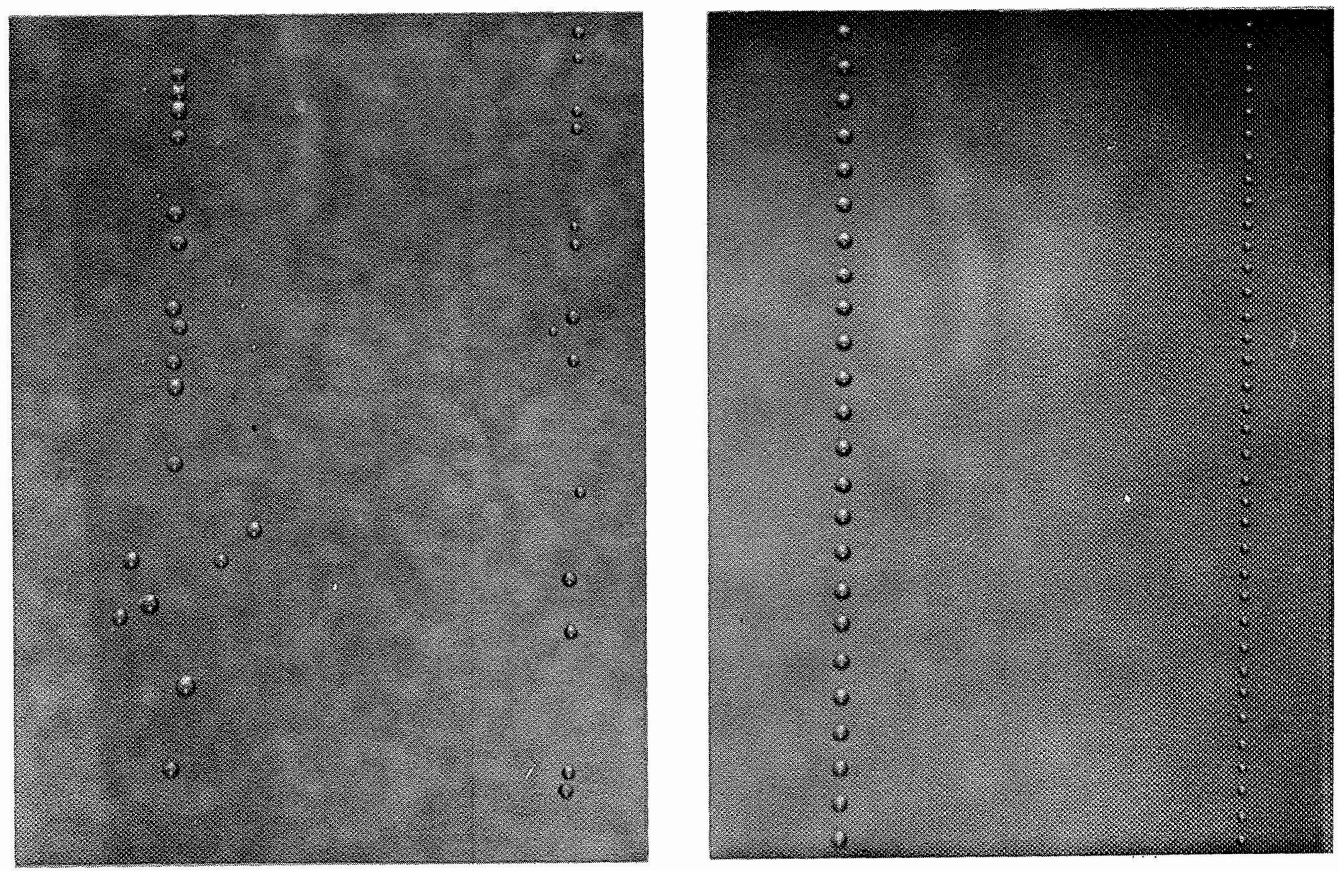


Figure 9. Simultaneously Generated Droplet Streams. From Left to Right, the droplets have diameters of approximately 650, 550, 500, and 300 Microns.



(a) Without Vibration (b) With Vibration

Figure 10. Effect of Oscillatory Disturbance on Jet Breakup.

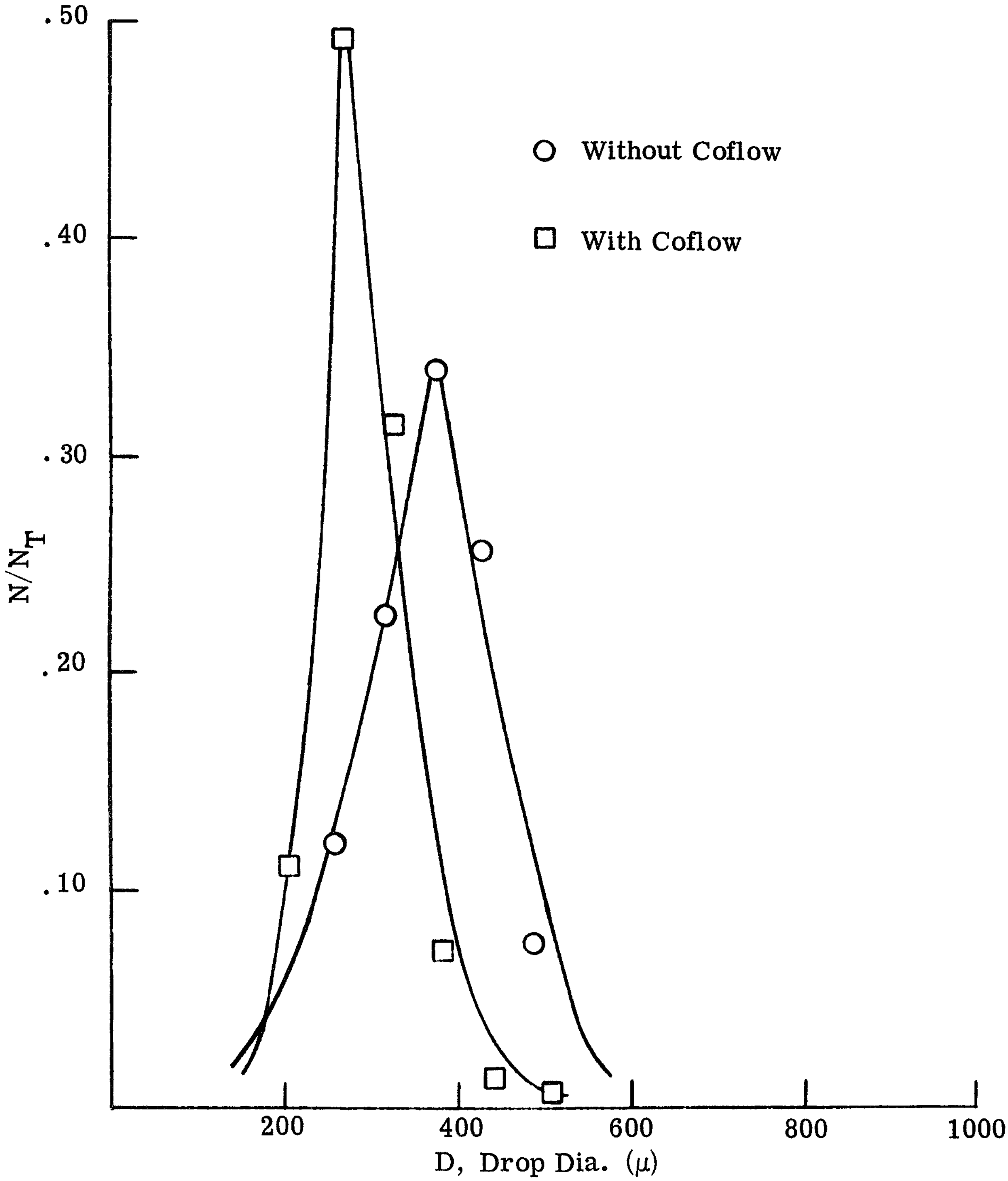


Figure 11. Effect of Coaxial Flow on Droplet Size Distribution 7 1/2 ft Below Generator Head.

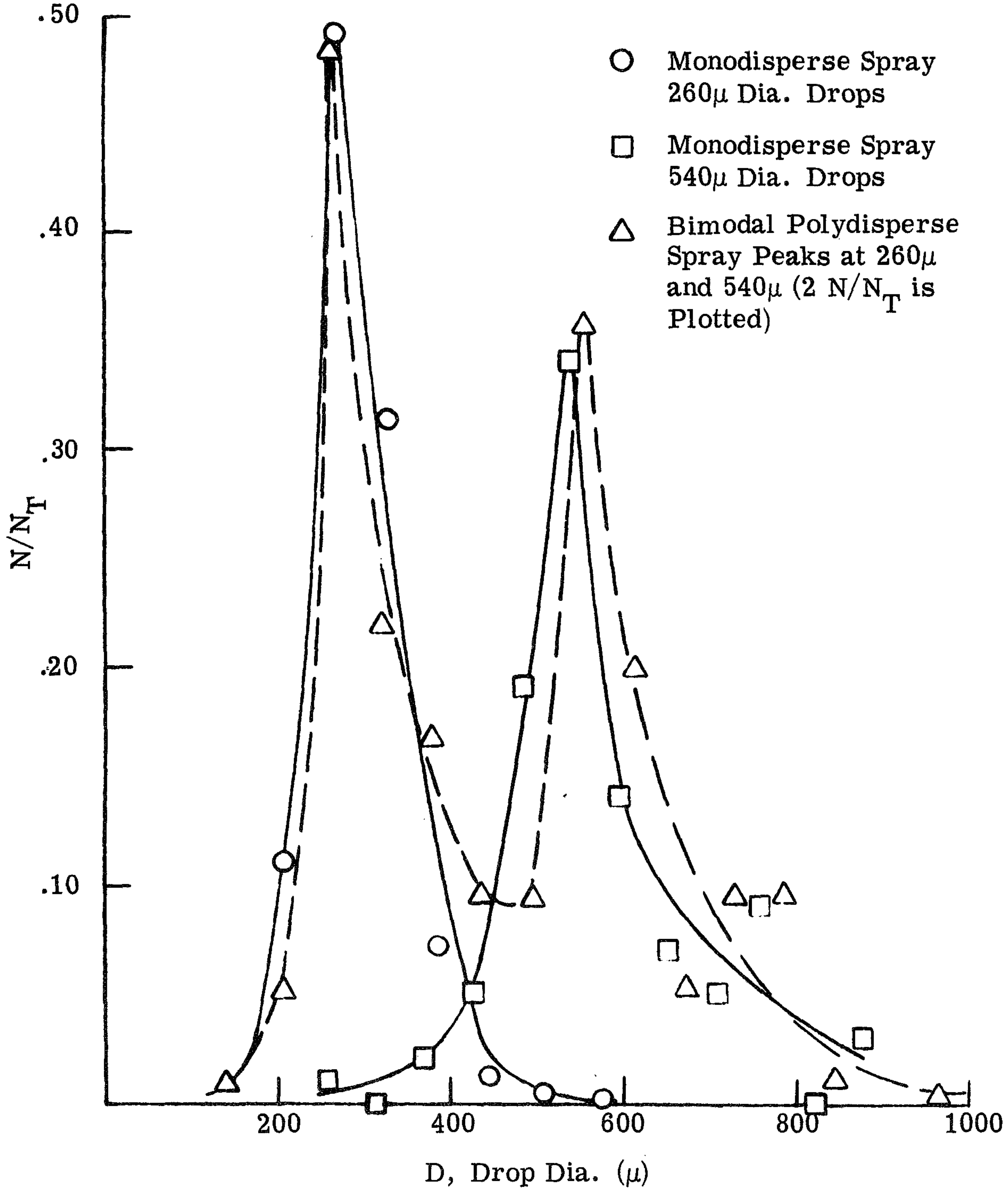


Figure 12. Droplet Size Distributions Achieved 7 1/2 ft Below Generator Head, All with Coflow.

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